Impedance Estimation of FEA's Grid in Fiji Islands by V-I Measurement by Using the Synchronous Reference Frame-PLL

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Abstract— **In recent years there has been a significant increase in distributed renewable energy generation feeding into the grid, with resulting detriment of the stability of the network, since present networks have not been designed for this purpose. To feed-in these renewable energy sources with minimum impact, it is essential to know a few grid parameters (voltage, current, grid impedance) at the point in which power supply is convenient. For this purpose in this paper an algorithm is proposed to obtain the estimated network impedance. This algorithm operates in time domain by a synchronous reference coordinate transformation, it requires only the measurement of the phase voltage with no-load and the voltage and current with a recognized load. This method has been applied to determine the grid impedance of the Fiji Electricity Authority (FEA) grid in Fiji (Viti Levu).**

Keywords— grid impedance estimation, distributed generation, grid stability.

I. INTRODUCTION

The impact of distributed renewable energy generation on the electrical distribution network as well as on the transmission network is crucial to power system stability due to their increasing trends. This has led up to many challenges to be dealt with to successfully implement a grid integration of renewable energy sources (RES). Among these the knowledge of the grid impedance seen from a Point of Common Coupling (PCC) plays a key role. These PCCs are defined as points in the network of public interest, electrically very close to the reference user, and they can be connected to other users. In general in the location of these points it is required to know the impedance network. This parameter affects the stability of the connection between the grid-connected power converters and the grid [1], and the related power flow [2] , the passive filter design [3], and active filter control [4].

The methods for grid impedance estimation published in literature can be divided into two categories: non-invasive and invasive methods. The non-invasive methods are passive methods which monitor signals already present in the system (line voltage, current, frequency …) by transducers and then try to evaluate the percentage of distortion that may undergo the parameters and evaluate, on the basis of this distortion, the variations of the network impedance. In this case, the main problem is that distortions could not be so large to be accurately measured, failing to give an exact estimation of the grid impedance: for this reason, passive methods have a very large non-detection zone (NDZ), which is their downside. On the other hand, the active estimation is based on the introduction of a disturbance at the point of common coupling, (PCC); the impedance value is then estimated on the basis of the response of the network. An overview of the methods is given in [5].

The most common active methods can be summarized into three groups according to the type of the disturbance. 1) The "transient current pulse" methods typically apply a pulse shaped waveform in correspondence of the crossing through the zero of the mains voltage. The estimation of the impedance can be obtained by evaluating the transient voltage that depends on the injection of the noise signal [6,10]. 2) The "non-characteristic sub-harmonics" methods inject inter-harmonics variable frequencies into the grid before or close to the PCC to estimate the grid impedance at different frequencies. The estimation of the impedance can be obtained by evaluating either the steady state [7] or the transient response [8]. A similar method uses an LCL filter in correspondence of an inter-harmonic: indeed, the peak frequency due to resonance is particularly sensitive to the variation of the impedance of the network. However, this method can only measure the network impedance at the resonant frequency and, in addition, the network model must be known in advance [3,11]; 3) finally, the "power variation" methods introduce both active and reactive power so as to cause a current variation and then evaluate the effects on the voltage and current: with the assumption that the impedance variation is linear, it is possible to estimate the value of the grid impedance [10].

In this paper an offline method based on power variation is proposed. The method requires two tests in which firstly the

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no-load voltage and then both voltage and current on a load between two phases are measured. This method has been described in [9] using a frequency domain approach, which requires the calculation of FFT along with its inconveniences. In this paper a modified version operating in time domain is proposed. It is based on SOGI-QSG (Second Order Generalized Integrator-Quadrature Signal Generator) [12-15] and a SRF-PLL (Synchronous Refence Frame-Phase Locked Loop). The method has been then applied to a weak network model in the island of Viti Levu in Fiji.

II. DESCRIPTION OF THE GRID UNDER INVESTIGATION

Fiji is a developing tropical island country in the Pacific Ocean, and has abundance of RES. There is an ever-increasing demand for electrical power and consequent need to harness as many RES as possible to meet the requirements. At present, the majority of energy is derived from Hydroelectric power (63%), but the fossil fuel based generation, mostly diesel generators, is steadily rising every year, whereas the renewable is still in the same position with resulting increase cost on the government annual budget, This increment of the demand might eventually increase the fossil fuel imports to an unsustainable level. Moreover, some of these diesel generation units do not operate at their peak values or are idle [16]. With this respect, the impact of the RES coming from the solar and the wind, has to be analyzed in the Fiji grid in terms of harmonic pollution, stability, voltage dips, load flow analysis and so on.

In order to carry out the analysis of the transmission network, an electrical power system modeling software, Electrical Transient and Analysis Program (ETAP), has been used in this work. ETAP is well-known for the analysis of a power system in terms of modelling, design, optimization, control, operation, and automation as well as for carrying out static and dynamic analysis of transmission networks [17].

The grid map from the FEA's annual report [16] for the year 2014 was used to extract the data needed to design the grid network. Other relevant information were retrieved from a report of KEMA on quantification of power system energy losses and loads in South Pacific utilities from 2012 [18]. Only the Viti Levu network has been analyzed and to design the network, average load ratings were used and a total of 145 MW of static load was added to the transmission network on different buses. The generation data extracted from the FEA's report showed a total of 217 MW of generation capacity [17].

The FEA power grid has 3 categories of power lines, the high voltage transmission lines with voltage ratings of 132 kV and of 33 kV, the medium voltage distribution lines with voltage ratings of 11 kV to 6.6 kV. The FEA report also highlighted the data for all the generating stations across Fiji, which were used in the ETAP network analysis [18].

After completing the network of the transmission grid of Viti Levu, the load flow analysis of the network was carried out. Fig. 1 shows the schematic of the electrical utility network of FEA in Viti Levu (main Fiji Island). The network, shown in Fig. 3, has a total of 71 buses, of which 14 are PV buses and 56 are PQ buses. The swing bus of the network is placed in Vuda. The schematic shown in Fig. 3 was created in ETAP to compress the whole network for clarity sake. Each composite block represent either a generation or a substation. These sub-systems are interconnected according to FEA's Grid map to form the overall transmission network.

Fig. 1. FEA's Power Network in Fiji (Viti Levu Island) [16]

III. THE PROPOSED METHOD

A. Theoretical fundamentals

The estimation of the network impedance has been made by using a method consisting of a simple implementation of the Kirchhoff's law for the mesh voltages, as shown in Fig. 2. It belongs to offline methods requiring a small amount of active power delivered from the grid.

$$\underline{Z}_G(\omega) = R_G(\omega) + j\omega L_G(\omega) = \frac{\underline{V}_1(\omega)-\underline{V}_2(\omega)}{\underline{I}_2(\omega)-\underline{I}_1(\omega)} = \frac{\Delta \underline{V}(\omega)}{-\Delta \underline{I}(\omega)}$$

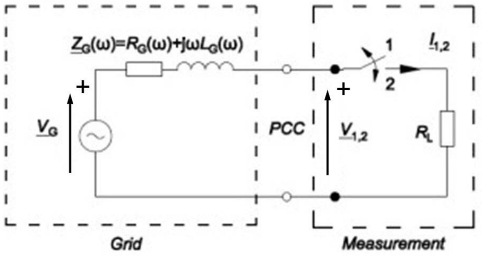

Fig. 2. Principle of the impedance evaluation

It should be noted that, although the described relations express a dependence on ω, in this work this dependence has been eliminated by performing a transformation of coordinates into a synchronous reference with a fictitious quadrature component (αβ→dq), to achieve a lower computational complexity than that of frequency domain methods which require a FFT to estimate the network impedance. For this reason in the following the parameters of interest will be indicated as phasors. It should be noted also that a known and constant load R_L is used in the time domain, so that the quantities of interest are dependent only on the change of the impedance of the network.

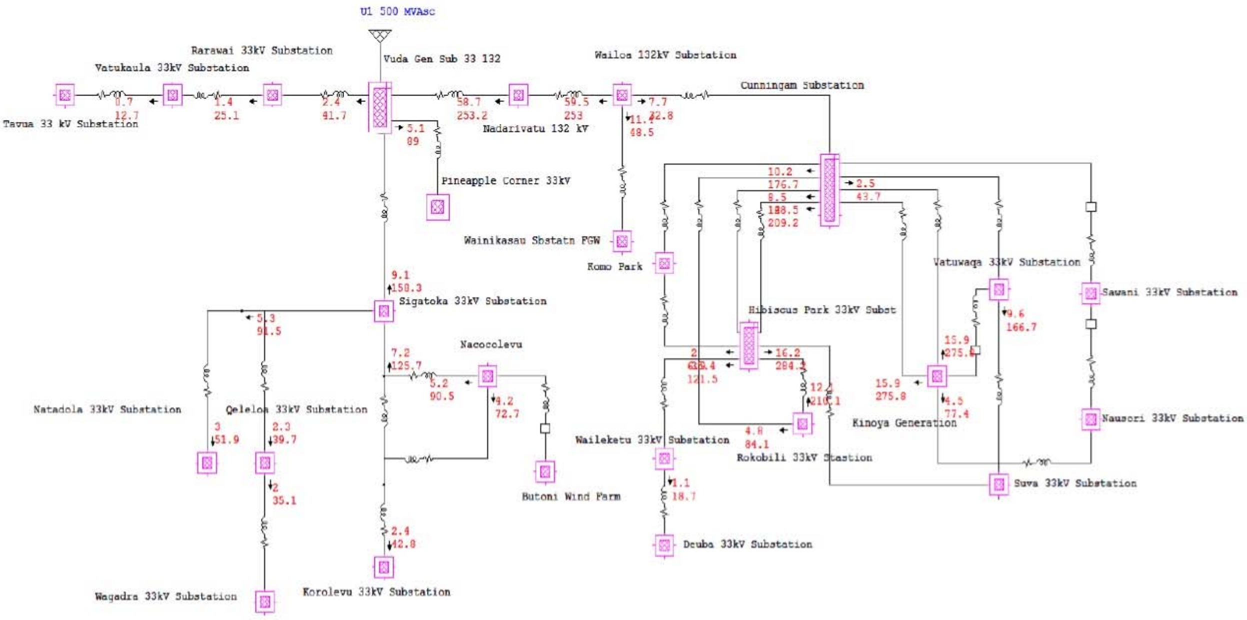

Fig. 3. Schematic of FEA's Transmission Network

Even if the system under test is three-phase, two phases at a time to obtain a behavior similar to a single phase system are considered; Fig. 4 shows the equivalent diagram used for a three-phase system.

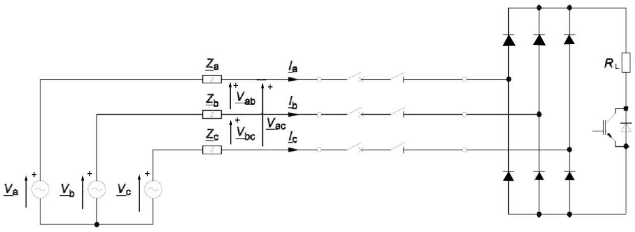

Fig. 4. Generalized phase diagram network used to estimate the impedance.

From the above it is clear that the algorithm implemented bases its operation on the measurement of three quantities: a) open circuit voltage grid; b) grid voltage under load (known and constant); c) phase current.

From the relationship shown in the single phase diagram it can be noted that the subscript indicates the value of the voltages to be considered: $V_{1,xy}$ indicates the phase-to-phase voltage (*between phase x and phase y*) on the PCC when the switch is open ($V_1 = V_G$ in this case and I_1=0), $V_{2,xy}$, voltages indicates the phase-to-phase voltages (*between phase x and phase y*) on the PCC when the switch is closed ($V_2 \neq V_G$ e $I_2 \neq 0$). Then the simple Ohm's law can be used to retrieve the parameters. By considering the closing and opening of various switches the following relationships can be obtained:

$$\begin{aligned} \underline{V}_{1,ab} - \underline{I}_{2,a}\cdot\left(\underline{Z}_a + \underline{Z}_b + R_L\right) &= 0 \quad & \underline{V}_{2,ab} &= \underline{I}_{2,a}\cdot R_L \\ \underline{V}_{1,bc} - \underline{I}_{2,b}\cdot\left(\underline{Z}_b + \underline{Z}_c + R_L\right) &= 0 \quad & \underline{V}_{2,bc} &= \underline{I}_{2,b}\cdot R_L \\ \underline{V}_{1,ca} - \underline{I}_{2,c}\cdot\left(\underline{Z}_c + \underline{Z}_a + R_L\right) &= 0 \quad & \underline{V}_{2,ca} &= \underline{I}_{2,c}\cdot R_L \end{aligned} \tag{1}$$

Where the open circuit voltages are measured when the load is disconnected. From (1) it is possible to get:

$$\begin{aligned} \Delta\underline{V}_{ab} &= \underline{V}_{1,ab} - \underline{V}_{2,ab} \\ \Delta\underline{V}_{bc} &= \underline{V}_{1bc} - \underline{V}_{2,bc} \\ \Delta\underline{V}_{ca} &= \underline{V}_{1,ca} - \underline{V}_{2,ca} \end{aligned} \tag{2}$$

The ΔV_{xy} thus obtained represent the variation of the voltage on the PPC from no-load to load conditions and allow the impedance value of the network to be evaluated by using the following relationships derived from (1):

$$\begin{aligned} \Delta\underline{V}_{ab} &= \underline{I}_{2a}\cdot(\underline{Z}_a + \underline{Z}_b) \\ \Delta\underline{V}_{bc} &= \underline{I}_{2,b}\cdot(\underline{Z}_b + \underline{Z}_c) \\ \Delta\underline{V}_{ca} &= \underline{I}_{2,c}\cdot(\underline{Z}_c + \underline{Z}_a) \end{aligned} \tag{3}$$

From (3) it is possible to compute the value of the impedances seen in the PCC as follows:

$$\begin{aligned} \underline{Z}_{ab} &= \underline{Z}_a + \underline{Z}_b = \frac{\Delta\underline{V}_{ab}}{\underline{I}_{2,a}} \\ \underline{Z}_{bc} &= \underline{Z}_b + \underline{Z}_c = \frac{\Delta\underline{V}_{bc}}{\underline{I}_{2,b}} \\ \underline{Z}_{ca} &= \underline{Z}_c + \underline{Z}_a = \frac{\Delta\underline{V}_{ca}}{\underline{I}_{2,c}} \end{aligned} \tag{4}$$

Where Z_{xy} indicates the impedance seen in the PCC between the *x* and the *y* phase. This value does not depend on the R_L.

From (4) the impedances for each phase can be retrieved as:

$$\begin{aligned} \underline{Z}_a &= \frac{1}{2}\cdot\left(\underline{Z}_{ab} - \underline{Z}_{bc} + \underline{Z}_{ca}\right) \\ \underline{Z}_b &= \frac{1}{2}\cdot\left(\underline{Z}_{ab} + \underline{Z}_{bc} - \underline{Z}_{ca}\right) \\ \underline{Z}_c &= \frac{1}{2}\cdot\left(-\underline{Z}_{ab} + \underline{Z}_{bc} + \underline{Z}_{ca}\right) \end{aligned} \qquad (5)$$

IV. STRUCTURE OF THE IMPLEMENTED ALGORITHM

The proposed algorithm uses the following three steps to extract the modules and phases of the measured parameters in time domain [1]: a) Generation of quadrature components; b) Coordinate transformations in synchronous reference; c) Coupling to the main frequency by PLL.

a) *Generation of quadrature components*

The quadrature component is obtained by a SOGI (Second Order Generalized Integrator) filter as shown in Fig. 5. In this scheme the v variable corresponds either to the measured V_{xy} voltage or to the phase current I_x. The gain *k* is used to determine the selectivity of the bandwidth of the SOGI filter (if *k* is less than unity a narrower band is achieved). This filter performs a double integration to generate two variables in quadrature *v*' and *qv*', that correspond to quantities V_α and V_β for example. It performs a double integration so that the phase difference between these two variables can be more accurate; this double feedback structure provides the phase angle used for the Park transformation as well as the central frequency [7].

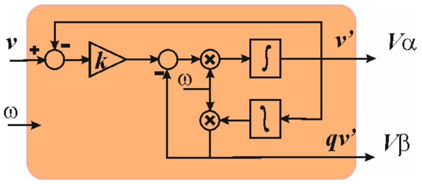

Fig. 5. General scheme of the SOGI filter (ω' is a reference pulse).

b) *Coordinates transformation to synchronous reference*

In order to transform sinusoidal quantities into constant values, thus avoiding the frequency analysis using an FFT or DFT, quantities in stationary αβ coordinates are projected into a new reference frame, the *dq* reference frame [7], rotating at angular speed ω equal to the pulsation of the input voltages or currents; for this purpose a Park's transformation is used.

c) *Coupling to the network frequency by PLL*

Since the algorithm performs an off-line evaluation, a PLL is used to force the system to get synchronized with the phase voltage pulsation. Since the network is studied as a single phase network as shown in Fig. 2, the scheme described in Fig. 6 is adopted where the dq transformation is performed. In this system *v* indicates the input variable, *v'* the phase variable, obtained as a reference, with *qv'* the variable in quadrature, and ω_{ff} indicates the rotating speed of the *dq* reference.

The variables *v'* and *qv'* are considered as the stationary *αβ* components from which the *dq* components, v_d and v_q, respectively, are computed [8]. The output variables from this system are needed both to guarantee that the frequency of the grid is picked, that is $f \cong f_{grid}$, and to know the phase of the input, θ_{PLL}, which is used for the estimation of the *dq* reference frame.

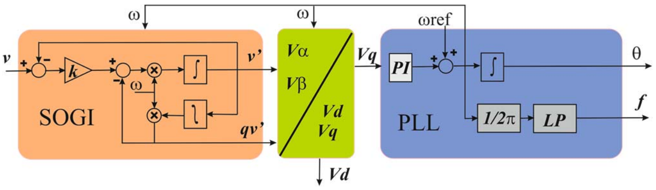

Fig. 6. General scheme of the system to obtain the quadrature component, and the PLL which outputs the frequency and the phase of the input voltages.

V. IMPLEMENTATION OF THE ALGORITHM IN SIMULINK® ENVIRONMENT

The scheme of Fig. 7 shows the Simulink implementation of the algorithm shown in Fig. 6 It contains the SOGI (left), the coordinates transformation (center), and the PLL (right). In the first part of the scheme the components in αβ coordinates are computed by the SOGI-QSG (Generalized Second Order Integrator-Quadrature Signal Generator filter) which generates a signal in quadrature with respect to the input signal. θ indicates the phase of the rotating reference frame and its value is obtained by PLL.

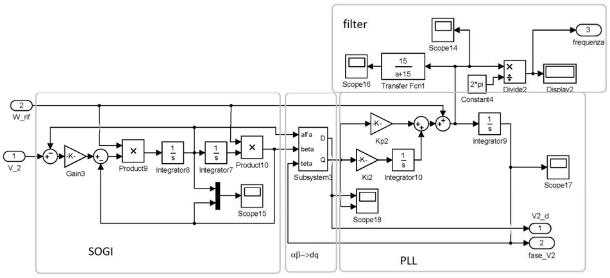

Fig. 7. Simulink implementation of the system to obtain the quadrature component, the frequency and the phase.

The scheme of Fig. 7 is repeated for all the other variables meaning: $V_{1,xy}$, $V_{2,xy}$ and I_x. The estimation of the network impedance is finally obtained by (4) and (5).

The transition from *αβ* components to *dq* components obtained by the Park's transformation is implemented in the "Subsystem 2" block, which also shows its subsystems. This block requires the knowledge of the phase of the input signal, and it is obtained by integration of the pulse coming from an SRF-PLL (Synchronous Reference Frame-Phase Locked Loop). Finally, it outputs not only the useful magnitude and phase signal, but also the value of the frequency to be synchronized. The following values have been chosen for the PI: k_p=1000, k_i=2000, it is a trade-off between speed of convergence and steady state error.

Some remarks should be made about the choice of the value of R_L, since it requires a trade-off between two extreme cases: 1) if R_L is very large ($R_L >> 0$), it may compromise the functioning of the whole algorithm, because in such conditions $V_1 \cong V_2 \rightarrow \Delta V \cong 0$ and as a result the impedance cannot be estimated; 2) if R_L is very small ($R_L \cong 0$), an unacceptable value of the current results, and the estimated values can be very different from the actual ones because $V_2 \cong 0 \rightarrow \Delta V \cong V_1$ corresponding to evaluating the impedance with the load voltage only.

In any case it can be remarked that R_L is a dissipative load, hence it is crucial that the time required for data sampling is as small as possible.

VI. RESULTS

On the basis of voltage and current measurements performed on the grid, the estimated impedance in some points of the grid have been evaluated. In Fig.s 8 and 9 examples of the time domain curves of the resistance and of the reactance are sketched. These curves are taken without filtering to show how the algorithm converges. It can be noted that only about 0.1 s are necessary (starting from a no-lock condition of the PLL); in this case the oscillation superimposed corresponds to an error of ± 10^{-6} Ω for the resistance and ± 10^{-4} Ω for the reactance. The use of a low pass filter reduces the oscillations, thus improving the estimation as shown in Fig. s 10 and 11, where the effects of a low-pass filter with a cut-off frequency of 15Hz and a discrete filter performing the mean over 500 samples are shown respectively. It can be noted that the use of filters makes the convergence time longer as expected. In any case this remains compatible with the time required to perform the measurements.

The following characteristic points have been selected for the analysis: 1) Vatuwaqa, 2) Korolevu, 3) Suva, 4) Wailoa.

Vatuwaqa has the most sensitive loads including the University of the South Pacific and three most busy commercial centres: Damodar city, Garden City and Sports City. In this area there are a number of offices and commercial shops, business centres and also the national stadium of the country. In a normal operation condition this bus is sensitive and critical due to low voltage profile.

The geographic location of Korolevu is situated half way between Suva and Sigatoka; two main cities of the country and it is the end point of the radial network. At this point the grid suffers from low voltage and it is marked as critical. Connecting 23 Km transmission line from Korolevu to Debua can solve the problem.

Suva is the capital of the country and full of various types of commercial loads. It is a port city and the main port power system is connected at this point. This point is very important as the main economic activities are conducted here. This sensitive point of the nation is served by Kinoya Power Generating Station to make sure that the point should remain stable at all the time.

Wailoa is the biggest hydro power generating station of the country. Almost 55% of the national power requirement is supplied by this station.

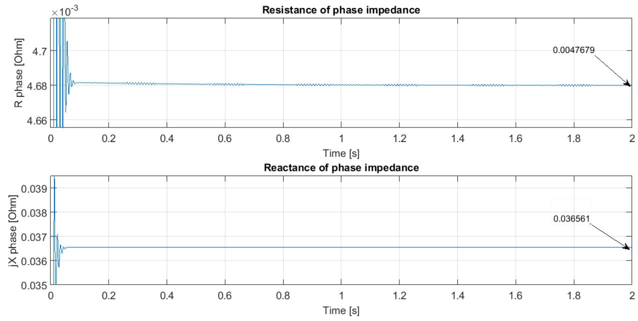

Fig. 8. Ttrend of the estimated impedance.

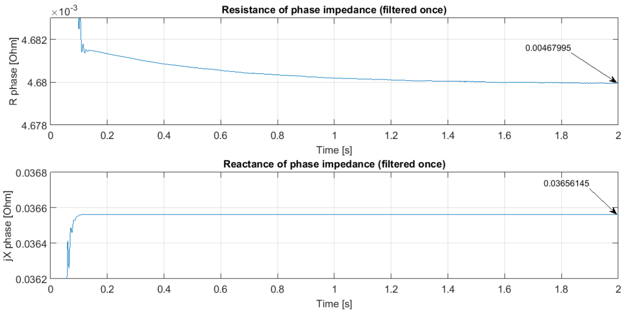

Fig. 9. Zoom of the trend of estimated impedance filtered once.

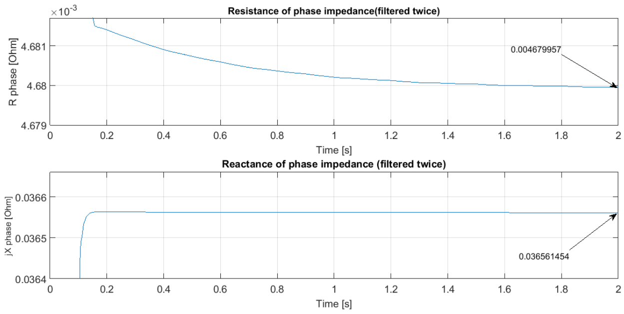

Fig. 10. Zoom of the trend of estimate impedance filtered twice.

Results are summarized in table I, where only filtered values are reported. In table II the maximum values of the no-load voltage, voltage and current with load and the energy lost in the load are shown. It can be remarked that even if the energy is calculated on the basis of a measurement time of 5s, this value can be reduced to 2s without relevant errors, moreover, a good approximation of the final value can be achieved with a measurement time of 0.2s without filtering the output signals. Finally, it represents the worst case since the load is considered as purely resistive. From the table it appears that the situation on Korolevu is very critical with high value of estimated impedance, due mostly to the inductance. This results in high voltage dips and low short circuit power and suggest that this point should be interconnected to the close one in Deuba. On the other side the impedance in Wailoa , which is a high voltage bus, seems the best point where renewable energy source might be injected without strong repercussions on the HV grid. The 2 other points in Vatuwaqa and Suva are still with rather high values of impedance, and account for the voltage fluctuations of these areas, in spite of being close to the diesel generators of Kinoya.

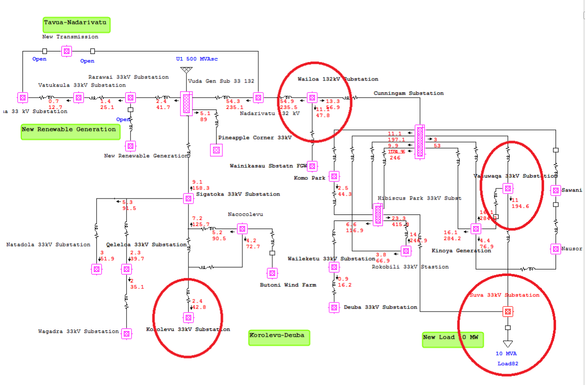

Fig. 11. Location of the points under investigation

TABLE I.

Point	Estimated Impedance			
	{Z} [p.u.]	*Re {Z} [Ω]*	*Im {Z} [Ω]*	*L [mH]*
Vatuwaqa	7.05	1.02	8.465	26.9
Korolevu	12.02	4.14	13.936	44.4
Suva	5.66	2.14	6.440	20.5
Wailoa	1.63	23.69	285.092	907

TABLE II.

Point	Maximum voltage and current with related energy required by a resistive load (t_{meas}=5s)			
	V_1 [kV]	*V_2 [kV]*	*I [A]*	*E [MJ]*
Vatuwaqa	11.11	10.75	205.3	5.5
Korolevu	11.44	10.77	128.4	3.4
Suva	11.5	10.75	279.1	7.5
Wailoa	139.2	135.7	76.4	25

VII. CONCLUSION

The implemented algorithm is based on SOGI-QSG and a SRF-PLL, it allows the estimation of the impedance to be simplified with a good approximation on the obtained values, without introducing disturbances on the grid. As a matter of fact it requires only the application of a resistive load for few seconds while the a priori knowledge of the network structure is not required. The algorithm is able to extract the fundamental and harmonic components of the electric parameters, it can be implemented in a cheap microprocessor for on-line estimation.

The results on the grid impedance estimation performed on FEA's Grid in Fiji Islands show that Wailoa seems the best place to inject energy from renewable energy sources, while Korolevu needs an interconnection to Deuba to decrease its impedance. Experimental measurements are being made and show a high THD of the voltages and poor power quality. This will be the focus of future work.

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